UPC 041

January 1979

Design of the Energy Doubler

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1. Introduction

Development of Energy Doubler magnets has been under way at Fermilab since mid-1972. This work has progressed to the point where dipole magnets with desirable design characteristics and reasonably good field quality have been built. The focus of the effort is now changing toward refinement of the magnet design and development of production methods to manufacture magnets of uniformly high quality in the quantities desired.

Some of the development magnets are being used for individual testing and for a trial installation for systems tests in the design location of the Energy Doubler below the Main Ring magnets in the tunnel. There has also been for some years a small parallel effort on the accelerator aspects of the design. This accelerator-design effort has intensified in the last months and there has now been a concerted effort to produce the elements of a design. This report summarizes the recent magnet and accelerator design work.

2. Energy Doubler Design Goals and Problems

The Energy Doubler is to be a proton accelerator with a peak energy of 1000 GeV and the capability to supply both external beams for fixed-target physics and internal stored beams for colliding-beam physics (both $\bar{p}p$ and pp). For fixed-target physics, both slow extraction over a few seconds and fast extraction over 1 msec are required. Intensities of the order of 2×10^{13} ppp are expected, although efforts are being made not to preclude higher intensities through any inherent design limit. The maximum repetition rate capability is approximately 2 cycles per minute (75 GeV/sec).

As a storage ring, the Doubler must be capable of storage lifetimes of about three hours for $p\bar{p}$ and shorter for pp collisions. One interaction region with an amplitude function β^* of 3 m (possibly going to 1 m) is planned. The 150 ft free space in the straight section is sufficient to bring 150 GeV protons from the Main Ring into collision with 1000-GeV protons in the Doubler and allow for a basic detector 33 ft long. Luminosities of 4×10^{30} cm^{-2} sec^{-1} are expected with beams of 2×10^{13} p in each ring. In the case of $\bar{p}p$ collisions, the beam will originally be bunched into a single rf bucket of the Doubler with 2×10^{10} p's and 6×10^{9} $\bar{p}$'s for a luminosity of 10^{28} cm^{-2} sec^{-1}.

Further developments, such as rebunching the protons in the Main Ring, increasing the number of filled buckets, lower β^*, better $\bar{p}$ collection and cooling could increase the luminosity to 10^{30}. The basic detector in the interaction region can be supplemented with additional detectors in the forward and backward directions because both beams are in the Doubler and the whole 150 ft of straight section is available for the detector.

The major design problems and limitations of the Doubler came from the use of superconducting ring magnets and the placement of the magnets within the limited confines of the existing Main-Ring tunnel. Even though the technical feasibility and reliability of a superconducting accelerator have not been unambiguously demonstrated at this time, it is important not only to point out the present state of understanding of these problems, but also to explore the more conventional aspects of the accelerator design so that available possibilities or options are not precluded.

The problems associated with the use of superconducting magnets can be categorized as follows: magnetic field, good-field region, uniformity, reproducibility and stability, sensitivity of the magnets to heating of any kind (eddy currents, beam loss), the necessity to protect the magnets from self-destruction if for any reason they should go normal, the large cryogenic refrigerator system necessary to keep the magnets at 4.6°K and supply the necessary cooling.

The major problems associated with the functional requirements of the accelerator are connected with extraction: sufficiently large magnet aperture for efficient resonant-extraction magnets, the need for both superconducting extraction magnets for slow extraction and warm pulsed magnets for fast extraction, shielding of the superconducting magnets downstream of the extraction septa from the unavoidable beam loss. For $\bar{p}p$ colliding beams, the following additional complications are introduced: the need for both forward and backward injection and abort systems, the need for independent rf control of the p's and the $\bar{p}$'s, an interaction region with four pairs of individually powered high-strength superconducting quadrupoles, chromaticity changes produced by the interaction region, and the need for detecting single rf buckets containing less than 10^{10} particles.

3. Magnet System

a. Magnets. The coils of the Energy Doubler dipoles lie on a 1.5-in. inside radius and the design good field region ($\frac{\Delta B}{B} = 10^{-4}$) is ± 0.8 in. horizontally and ± 0.6 in.

vertically. A single pass of the beam through a few magnets at displacements of 1 in. horizontally and 0.8 in. vertically can be contemplated if some distortion of phase space is tolerable, such as in single-turn injection, extraction, or abort. The quadrupoles are constructed on a 1.75-in. inside radius and have a good design-field region out to 1.25 in. and so are never as restrictive as the dipoles.

In the high-field superconducting magnets of the Doubler, the coil-conductor placement plays the major role in the determination of magnetic-field quality and reproducibility. Unlike conventional iron magnets, where a high degree of reproducibility can be obtained by the use of laminations stamped from a precision die and the magnets fabricated easily from these laminations, great care must be taken in the coil fabrication of superconducting magnet to minimize field variations. Even so, we expect considerably larger variations than in conventional magnets and consequently the Doubler will have correction coils capable of error compensation at full magnetic excitation. Motion of the coils during excitation or changes in coil placement after quenches or warmup-cooldown cycles must also be considered and allowed for in the correction package.

The peak field in the magnets and the heating of the coils during ramping is a function of the insulation on the individual strands of the conductor cable and clamping pressure on the coils. Continuous monitoring during magnet fabrication has been necessary in order to obtain the required peak excitation and low ac loss.

At the present time about one-third of 29 magnets with type 5 collars (between serial numbers 93-138) measured do not go to the 1000-GeV excitation level during magnetic measurements. Measurements of ac losses on Zebra and Ebonol cable indicate that losses of about 500 Joules/cycle can be expected for ramps to full excitation and ramp rates up to 400 A/sec. It is possible that if the ac losses could be kept as low as 300 to 400 J/cycle, a 2 cycle/minute repetition rate might be achieved with the 966 W of refrigeration available at each service building.

Instrumentation to measure integral magnetic length precisely is being developed. In the meantime NMR data measured over the length of the magnet indicate integral field variations of order $\pm 10^{-3}$. More worrisome are the measurements of vertical axis of the dipole magnets. The vertical plane changes angle by 0.2 to 1 millirad when repeated measurements are made of one magnet through warm-up and cooldown. Repetitive measurements of many of the magnetic parameters have now been made, and comparison of ac and dc harmonic data exists, although the indication is that ac data are not very reproducible.

The large negative sextupole moment of the dipoles has been reduced to zero. However relatively large fluctuations from magnet to magnet in the multipoles through the 12th pole continue to be a problem. There are still not sufficient data from magnets incorporating the recent design changes and sufficient knowledge of the accuracy and reproducibility of the measurements to unambiguously choose the proper ranges of the correction coils. Errors summed over all multipoles usually are less than 25 G at 1-in. radius at 40 kG excitation.

The new two-shell quadrupoles are presently being manufactured. The first such quadrupole is now in the magnetic-measurement process.

b. Power Supply and Magnet-Protection System. The power supply system is similar to that used for the Main Ring and should not present any real problems. Unlike the Main Ring, dipole and quadrupole magnets are connected in series in the Doubler, because of the difficulty of carrying separate leads for the bend and quad circuits through the magnet cryostat system and the expense in helium and power of bringing leads out to a conventional bus system. The series system means not only that care must be taken in the initial determination of the relative strengths of the bend and quad magnets, but also that complete flexibility in the choice of accelerator operating point no longer exists. Large correction quadrupoles of the order of 5% of the main quadrupole strength will be necessary in order to do modest exploration of the tune diamond and tune adjustment as the interaction (low-β) region is turned on.

Six 2 kV supplies distributed around the ring are planned to supply voltage for a 75 GeV/sec ramp rate. A single holding supply of low voltage will maintain the 4250 A necessary for flattop.

The magnet string is connected in series all the way around the ring and at the ends a return bus that is an integral part of the magnet coil folds back through all the magnets. Voltage between the return bus and magnet coil will be at least 1 kV during ramping for magnets near the power supplies. Transients may generate much larger voltages if care is not taken to damp transmission-line modes. The large voltages between the return bus and rest of the coil are worrisome because of the lack of space for insulation. If problems of shorts do appear, it is possible to double the number of supplies and consequently reduce the peak voltage.

Delay-line modes have been studied and damping resistors across each half cell (4 bend magnets and one quad) will be required. Terminating resistors between the return bus and ground at the turnaround points may also be necessary. The delay-line effects can be minimized if the coil-to-bus turnaround is electrically equidistant from adjacent power supplies. On the other hand, it would be convenient if the turnaround were located at the interaction-region straight section to minimize interference between the accelerator and detector at this point. Further consideration of the location of the supplies is necessary.

The magnet system must be protected against the inevitability of some number of magnets quenching because of failure of the magnets to withstand the requisite current or rate of rise, failure of the cooling system, or because of heat generated in the magnets by beam hitting them. Obviously most of the 360 MJ of energy stored in the magnetic field must be removed and only a small fraction can be dissipated in the magnets. Even so, care must be taken so that the energy is distributed uniformly enough so that local hot spots do not damage or melt the magnet conductor. The cryogenic system must also be able to withstand the helium pressure generated in these quenches. The half cell is taken as the minimum electrical unit that can absorb its own stored energy if some part of it goes normal and the main current is shorted around it. The energy is distributed by firing heaters in each of the four bending magnets, causing them all to go normal as soon as possible after a quench is detected.

So far, tests of the protection system have only been performed on a single string of 4 bending magnets ramped to currents of 2500 A because of the inability of the magnet cryostat to withstand pressures generated by higher-current quenches. When magnetic measurements are made, energy is removed from the magnet by a resistor system. Consequently the magnet and cryostats are not subjected to the full stress of a quench.

The magnet single-phase pressure relief tube system has been redesigned so that higher-current quenches can be absorbed and tests of the first modified magnet have been successful. Full-energy quenches have been carried out without deterioration of field quality. A redesign of the heater quench-detection systems is also being implemented so that less energy will be dumped before the heater causes a distributed quench. A number of magnets with the revised relief system will be installed at B12 and tested to high current in the near future. In the meantime, we do not know if a half cell can withstand a full field quench, if the quench could propagate from one half cell to adjacent ones, or whether the return bus is sufficiently protected.

c. Refrigeration System. Each satellite refrigerator will feed approximately 1/24 of the ring (32 dipoles and 8 quads) in two parallel flow circuits. The feed boxes are located at the quads just below the service buildings and turnaround boxes consisting of a warm beam-vacuum isolation gate valve and two JT valves are at the quads approximately equally distant from two service buildings. The space required for these boxes reduces the space available for correction coils by about 20 in. at 7 out of 32 quad locations in a sector. The choice of where the turnarounds are located is thus strongly coupled to the correction-coil scheme unless one is willing to give up some of the bend length at every half cell to give sufficient correction-coil space at every main quad.

The measured heat load of the dipole is 8 to 9 W dc and 400 to 500 J/cycle ac. With 24 satellite refrigerators, at nominal capacity, each supplied with 92 ℓ/hr helium from the central liquefier, cooling of the ring magnets and correction coils should be sufficient for 1 cycle/minute or faster. With only three-fourths of the refrigerators or without the central liquefier, operation will be severely limited.

The compressor system for the satellite is to be located at six service buildings (zero buildings). These 24 compressors should give each satellite 966 watts capability with the the central system operating.

Two satellite refrigerators are now installed, at A1 and A2. The A1 refrigerator has been operating with a 20-dipole, 5-quadrupole string for the "minisector" test. The magnet string was cooled, with the ends below 6K and the center at 4.7K, although the system was not filled with liquid helium.

The design of the double turnaround boxes is just underway. One of the problems will be the necessity of passing the superconducting bus from one helium-flow system to another. Also underway is the design of bypass systems for the warm regions. There are two short bypasses and the long straight section bypass per sector. Care must be taken to make the warm part of these regions as long as possible so as to use them efficiently.

d. Vacuum System. The magnet vacuum system is divided into two parts, the bore-tube vacuum and the insulating vacuum. The bore-tube vacuum is very simple, with a single seal and bellows between adjacent magnets. The discontinuity in the beam tube caused by bellows is covered by a shield and adjacent magnets connected by rf fingerstock between the bellows shield of one magnet and the next magnet. This shield and fingers cause considerable difficulty during installation and will also make it very difficult to move one magnet laterally with respect to another for alignment. Because the bellows do not seem to add sufficiently to resistive-wall beam-power loss, the shield may possibly be left out.

The bore tube is at helium temperatures, so pressures of the order of 10^{-11} Torr are expected in the cold region. Bore-tube seals between magnets separate the insulating vacuum from the bore-tube vacuum, which must itself be better than 10^{-5} Torr from insulation requirements alone. Leaks at these seals should not be a problem. The bore-tube seam weld separates the single-phase helium from the beam vacuum. Consequently it is the main probable source of vacuum leaks. Liquid-helium leaks at cold temperatures tend to have a much larger leak rate (of the order of 10^3 times) than the same leaks at room temperature, so adequate testing can be done only with a sensitive test procedure. This procedure is not being performed at present. Leak-rate measurements are not yet made when the magnets are cold on the magnetic-measurements stand. Equipment is presently being assembled so as to allow these checks to be made on each magnet as it is magnetically measured. Probably the worst pressure the beam will see is from the warm regions, where special devices like kickers, septum magnets, etc. will inevitably create high-pressure regions.

The insulating-vacuum connections of the magnet cryostats are quite complicated. Three liquid-line connections (2 He, one N) and the bore-tube connection are contained within the outer flange bellows and seal at each magnet end. During leak hunting of a string of magnets in the tunnel, an internal leak can be isolated to a particular magnet end joint and to a particular liquid system but a defective seal cannot be separated from a defective bellows, or a cryostat weld leak. Defective nitrogen bellows have caused considerable difficulty in the installation of the 25-magnet minisector. Experience here has clearly indicated the necessity of very careful leak checking prior to tunnel installation. The need for careful alignment during cryostat fabrication of the liquid lines at the magnet ends was also illustrated by the difficulties encountered when connecting magnets.

e. <u>Tests</u>. Tests of doubler systems and components are being performed at the Magnet Test Facility, B12 (the Awning), in the minisector, and in the Switchyard. At the test facility, cycling tests on individual magnets are under way, as well as development of the low-impedance pressure-relief system. At B12, tests on helium leaks through the bore tube, quench protection, pressure induced during quenches, measurements of heat leaks, and power supply development are all underway for a 4-dipole string. In the minisector, installation problems related to magnet positioning, hookup, vacuum integrity and checking, and cooldown of the string are being confronted and single-pass injection beam studies are proceeding. At Switchyard, two magnets are used to measure the amount of beam loss at which the magnets will no longer remain superconducting.

Both the tests at B12 and the minisector are somewhat hampered by lack of good quality magnets that have proper quench heaters, low ac-loss conductor, low-impedance relief systems and adequate peak-field characteristics.

A complete system lifetime test of a 20-magnet string is planned for this year. Because of the difficulty of working on such a system in the tunnel, it is planned to install this string at B12.

In the minisector test, progress to date has resulted in installation of 25 magnets. This string has been made leak-tight and cooled sufficiently for the magnets to be superconducting with an excitation of 425 A. Beam was injected into the string and the magnets were observed to quench. The amount of beam was insufficient to register on the beam-position detectors and no beam was observed at the end of the string.

4. Accelerator Design

a. Lattice. The magnet lattice has gone through an evolution over the past six months as the requirements of the design have become apparent. The original lattice followed that of the Main Ring very closely. The only changes were those necessitated by the difference in bending magnet length (the Doubler magnet is 22 ft overall length instead of 20 ft, 11 in. for the Main Ring) and the change in tune (19.4 instead of 20.3 as the Main Ring was originally designed). The use of 22-ft magnets considerably shortened the available free space in an average cell, from 72 in. to 34 in., even though the superconducting quadrupoles are considerably shorter than their Main Ring counterparts. This free space is needed for beam detectors, correction coils, vacuum pumpouts and, in some locations, cryogenic and power feeds and cryogenic turnarounds. Because of the small amount of free space, some of the correction coils are inside the main quadrupole. The half cell, which consists of a quadrupole and four bending magnets, was arranged so that the bend center of the four magnets comes directly below that of the Main Ring. During installation, it has been found that it is more difficult to work on this center joint than any other, because it comes directly at a Main-Ring magnet support point (the Main-Ring stand must be replaced with a new modified stand to allow work at all).

Analysis of extraction made it apparent that a redesign of the two straight sections involved was necessary, because without this change the aperture of the Doubler magnets would not permit efficient extraction. This redesign called for large horizontal β at the front of the straight section (225 m instead of 50 m) and could be accomplished by reversing the polarity of the straight-section doublets, changing their position and length and also changing the length of the two adjacent quads. In this scheme it was necessary to replace one bending magnet on each side of the straight section with two half magnets, one of which went between the quad doublet.

A preliminary design of a low-β region for both pp and $\bar{p}p$ interaction has been worked out. It leaves about 45 m of the original 50-m space available. For β^* less than approximately 10 m, both β_{max} and η_{max} grow large, with the result that at $\beta^* = 1$ m, $\beta_{max} = 2500$ m and $\eta_{max} = 22$ m. Work on correcting the chromaticity, evaluating the off-momentum parameters, and so on, is just under way but it seems likely that difficulties may arise at a β^* value of 1 m.

Consideration is now being given to a lattice that uses shorter overall bending length, two 20-ft bend magnets and two 22-ft magnets in a half cell. The bend center of the doubler is changed slightly with respect to that of the Main Ring so that interference at the Main-Ring stands can be reduced. The free space now becomes about double what it was before. At the straight sections, much more flexibility is obtained; not only can high β for extraction be achieved without splitting doubler bend magnets, but a low β^* (approximately 11 m) sufficient for a pp interaction region can be obtained without extending into the straight section region at all and with a relatively small change in η. Presumably the flexibility for producing β^*'s of 1 to 2 m for $\bar{p}p$ collisions will also be increased, although no analysis has been done as yet.

The circumference of the Doubler must be adjusted relative to that of the Main Ring for pp collisions in order that the transit time of the different-energy particles is the same. A 1-cm larger radius of the Doubler will allow both beams to be on center for 200 GeV x 1000 GeV. At 150 x 1000 GeV, the Main Ring would have to store beam of an off-momentum orbit of $\frac{\Delta p}{p} = -0.3\%$. Beam to be injected into the Doubler on axis would run in the MR at $\frac{\Delta p}{p} = +0.38\%$. At present, the Main Ring does not operate well at this large positive momentum offset.

b. Correction and Adjustment Elements. The functions of these devices are: correction of both random and average error fields throughout the ramp cycle, exploration of the operating point and aperture, adjustment of the orbit and η function for injection, creation of suitable multipole harmonics, orbit and tune conditions for extraction, adjustment of the tune, chromaticity and other specialized corrections for the low-β^* interaction region. With the exception of dipole corrections, the random-error corrections are small compared with all of the other requirements. Elements that are considered necessary at present are dipoles, quadrupoles, sextupoles, octupoles and skew quadrupoles.

Trim magnets in the quad package include a dipole (horizontal or vertical), a sextupole, and octupole, all built concentrically inside the main quad and a 10-in. trim quad in the available free space around the beam detector. Some data are now available on construction problems and field quality of the trim elements. In the prototype, the quench currents of trim elements inside the quad are much lower than the design value.

Shunt supplies on the main quadrupole and bending magnets have been considered and may be advantageous for specific uses like the high-η region for stacking or for an extraction-orbit bump. For more general applications, there are arguments against using them. The supplies would have to float from ground and go up and down with the ramp by ±1 kV at some locations. They would have to produce both positive and negative current across an element which itself has positive and negative inductive voltage drops. Failure of individual supplies might bring down the whole main power system. For horizontal dipole steering, shunt supplies would work, but different coils and power supplies must be developed for vertical correction anyway. For quadrupole adjustment of a tune by $\Delta\nu = 0.05$, 100-A shunt currents would be required in each quad. Ripple requirements for extraction suggest the necessity of a minimum number of series quad circuits for tune adjustment. At the present time 200-A short leads are being installed across each quad so control of either bend or quad will be possible. As long as the leads do not overload the refrigeration system, having them available may be useful for yet unspecified needs like a large phase advance change over a small fraction of the ring or individual quad correction.

The dipole corrections may be inadequate. The issue hangs primarily on two things, whether the quad magnets can be moved relative to the bend magnets and whether the main dipole vertical axis of rotation is stable under quench and warmup-cooldown cycling. Data on the vertical axis that have been taken indicate changes of 1 mrad down to 0.2 mrad in one magnet as measuring techniques were refined and thermal cycling progressed. Repeated measurements on different magnets are required, but if changes of 1 mrad are real, moving magnets to adjust the equalibrium orbit is futile.

The standard prescription of moving quadrupoles off center to fit the high-field orbit is neither attractive or easy in the Doubler. At present, the vacuum-chamber shield at the magnet ends make it impossible to move one magnet with respect to another. This shield will probably be removed and we must find out how much motion can be made before other bellows restrict it. Unfortunately, whether the quads alone are moved or whether the bends are moved along with the quads, some bookkeeping will be necessary to insure that the bend axis does not get out of line with the beam and reduce the effective aperture. If the dipole trim strength were increased a factor of two, there would be a good probability of obtaining an equilibrium orbit without moving the magnets.

Quadrupoles must be strong enough to control the tune as the interaction region is turned on ($\Delta\nu = 0.44$). The present quadrupole strength is just sufficient for one interaction region if the tune is changed throughout the rest of the accelerator. If it is changed only in two-thirds of the accelerator or if two interaction regions can be made, then more quad strength is necessary, even though the correction quad is already 4% of the main quad strength. Trim quadrupoles will be powered in two series circuits for tune adjustment. Other circuits will be necessary for harmonic adjustment.

The necessary sextupole correction may be as large as three times the natural chromaticity. Both the large sextupole field errors and the requirements of colliding beams may make it advantageous to power the sextupoles individually.

Octupole circuits will be connected in series circuits for zero and 39th harmonic generation and correction for extraction.

If the short magnet lattice is adopted, it will probably be possible to remove the octupole and sextupole from inside the main quad and increase the trim dipole. Construction problems and banding for one trim element should be simpler than for three tightly packed trims. A system of fewer elements in specific locations could probably be worked out and the overall number of elements reduced. Presently, a space of 20 in. is available for special elements at locations where cryogenic feed and turnaround points do not occur. In the short lattice, there would be more space for special elements or unspecified devices that are found to be necessary to make the machine work.

c. Detectors. The present position-detector design has a horizontal detector at a horizontal focusing quad and a vertical detector at a vertical quad. Both horizontal and vertical detectors at each quad could make for better use of the magnetic aperture. More important, however, is the realization that single rf bunches of stored beams cannot be detected with the present electronics. Differentiation between p and $\bar{p}$ orbits at some places may require stripline detectors. Further development of position detectors for storage-ring modes is necessary.

d. The RF System. New cavities operating at the Main-Ring harmonic number (1113) will be designed for the Doubler so that they can fit between the Main Ring and the floor. They will be 1 ft in diameter and 9.25 ft long with an accelerating gap at each end (160° apart in phase). A spacing of half a wavelength between adjacent cavities will be possible. The drift tube, which is in the vacuum system, will be internally water-cooled along its length by a spline-like set of cooling passages. The cavities will be fed by coaxial lines from power amplifiers located outside the tunnel. No ferrite tuners are planned. Beam-loading stability will be obtained through beam feedback control to the power amplifier. Voltages of 250 to 380 kV (nominal 360 kV) per cavity are expected and 6 cavities should be sufficient for 75 GeV/sec acceleration.

The arrangement and spacing of the cavities is determined by the needs of $\bar{p}p$ acceleration and storage. Orthogonal control of p's and $\bar{p}$'s is probably required and the possibility of longitudinal adjustment of the interaction point is desirable. If the two cavities of a pair are placed $3\lambda/4$ apart center to center with $\lambda/4$ time phase between them, unilateral acceleration of either p's or $\bar{p}$'s can be obtained. Thus, with 8 cavities more than 1 MeV of acceleration voltage could be obtained for each beam. For fixed-target physics the full 8 cavity voltage would be available by rephasing. The space required for 8 cavities arranged in 4 unidirectional pairs is 25% more than if they were tightly packed and uses a total of 28.3 m.

e. Injection. The single-turn injection to be used in the Doubler should present no problems. The Doubler is located just under the Main Ring and phase-space matching is automatic. Transfer from the Main Ring to the Doubler will be done by Lambertson septum magnets located in a long straight section to produce the necessary vertical dog-leg between the two accelerators. These magnets will be preceded and followed by single-turn kickers to deflect the beam into and out of the transfer channel. Of necessity, the Lambertson septum magnets are positioned close to the center of the doubler aperture and there may be some benefit, especially during storage, in moving them out of the beam after injection.

An injection energy of 150 GeV will not place any burden on either the kicker or septum-magnet design and gives fields in the Doubler magnets for which the relative error fields are similar to those at high energy.

The kicker wave form for fixed-target physics (full ring) must be 21-μsec square pulses with short rise and fall times so as not to disrupt the beam on preceding or following turns. For $\bar{p}p$ injection, the wave form requirements are quite different if the injection of one type of particle is not to interfer with the other. We expect that for both $\bar{p}$'s and p's, single rf bunches will be injected with about 1.1 μsec spacing. The relative timing between the different bunches will be set up in the Main Ring by proper rotation of bunches in the Main Ring relative to the doubler. With some spacing conditions, e.g. for interactions at more than just two opposite straight sections, the $\bar{p}$'s should be injected first because the Doubler kicker for them is located next to the long straight section and protons already in the ring at this straight section would be kicked out. The Doubler kicker for p's is located 210 m from the straight section and so rise and fall times of the order of 0.4 μsec can be used.

Momentum stacking in the Doubler has been considered and may be possible if an η bump can be generated in the region of the septum by the regular correction quadrupoles or quad shunt supplies. It will produce a large local distortion of the off-momentum orbit so that space for the septum can be obtained without large beam excursions in the rest of the accelerator.

f. Abort System. In the Doubler, the abort-system design is strongly interwoven with many of the other aspects of the accelerator. When done in the most straightforward way it becomes an engineering task of nontrivial magnitude.

First, note that two abort systems of some sort are necessary. The one for protons should extract the beam from the accelerator. A scraper absorber of the kind used in the Main Ring would produce enough spray to quench downstream Doubler magnets. On the other hand, a dump block onto which the beam is kicked would probably be destroyed by the highly focused beam. In either case, induced radioactivity would be a personnel problem. The $\bar{p}$ abort can consist of a block onto which the beam is kicked, at least originally, but something must be provided.

If the forward (p) abort system is to be completely contained in one long straight section and the preceding 6-m short straight, 22 m of 2-kG fast single-turn kicker is required preceding a conventional extraction channel to a dump outside the tunnel enclosure. Building such a system would be a considerable undertaking, but the benefit of having the complete system in one straight section is considerable.

A less ambitious system calls for a 6 kG-m single-turn kicker located one long straight section upstream from the abort extraction channel. The beam must oscillate for 3-1/4 periods at large amplitude before it is extracted from the ring. The size of the good-field region thus limits the tolerable size of beam that can safely be aborted if no loss in the superconducting magnets is to result. Keeping in mind the fact that the beam is probably being aborted because there is something wrong with it makes this sound a little marginal.

Both the above systems require that all abort devices be ramped from injection to extraction excitation, including the kicker stored-energy system. A plan still needs to be developed that will provide reliable fail-safe operation, either by monitoring that the abort is operational at all energies or by devising a second-level backup abort. No estimate has yet been made of what happens if all the beam is lost in the accelerator.

Further complications arise when stored beam are considered. As the interaction region β^* is turned on, the phase advance in the rest of the accelerator must be lowered by $\Delta\nu \sim 0.4$ in order to maintain a fixed operating ν value. This means that either the phase advance between the kicker and extraction channel will be lowered by about 26^o and adjustments made for this in the abort extraction straight section or that the phase advance in this sector is held constant and that in the other sectors reduced even further. In either case, the tune adjustment must be made by the correction quadrupoles and represents a substantial fraction of the main quad strength.

A $\bar{p}$ abort with both kicker and dump block in one straight section does not seem possible. So here again the kicker for $\bar{p}$ will go in the long straight section preceding the one in which the dump is located. In this case, the change in phase as the interaction region is turned on is not as important because the beam is going into the front surface of a scraper. The hazard of traversing one-sixth of the ring with large oscillations is also reduced because of the low intensity.

Note that neither p's nor $\bar{p}$'s can be in the region between the two kickers when they are fired or the particles will be kicked by both devices. This means that if the p abort channel and $\bar{p}$ abort dump are located in one straight section, then the kickers are two straight sections apart. One third of the ring circumference is then excluded for use in $\bar{p}p$ storage and the interaction region straight section must be opposite the abort straight section.

The same kicker or a pair of kickers in one straight section could in principle be used for kicking both p's and $\bar{p}$'s. More work is necessary on this plan.

g. Extraction. Beam extraction from the Doubler for fixed-target physics is one of the two primary accelerator functions and the one which seems most at odds with the superconducting system. The original analysis of the extraction process was done using a lattice almost identical to that of the Main Ring. Under these conditions, the Doubler dipole aperture did not appear to be large enough for efficient, reliable extraction. A redesign of the lattice with a modification of the amplitude function β in the two long straight sections used in extraction now indicates that well-behaved extracted beam can be achieved without change in magnet aperture or at most change in only a few magnets. Inefficiencies of less than 2% are expected.

Slow resonant extraction could be done either on the third integer ($19\frac{1}{3}$) with 58th harmonic sextupoles or on the half integer ($19\frac{1}{2}$) with 39th harmonic quadrupoles and zero or 39th harmonic octupoles. The appropriate harmonics for slow extraction will be generated by the correction coils. Half-integer extraction appears to be slightly more efficient than third. It is also much easier to use for fast extraction, where one uses fast (warm) harmonic quadrupoles rather than sextupoles. The phase advance in a sector is approximately 3.25, just right for generation of the 39th harmonic if warm areas are available at the correct phase. Note that for fast third-integer extractions, the tune of the accelerator must be exactly 1/3 to extract all the beam, whereas in half-integral extraction all that is necessary is to increase the extraction quads by whatever value one wishes to obtain the appropriate spill time. Multiple-pulse fast extraction should be no easier for one-third than for one-half, but multiple pulse fast extraction has not yet worked well in the Main Ring and there are intrinsic problems that may not be soluble if very high extraction efficiencies are required. Error fields in the Doubler dipole magnets have so far been predominantly sextupole and it seems reasonable, although not essential, to choose for the extraction multipoles those that do not have large error components in the main magnets.

Taking the preceding issues into consideration, half-integer extraction will most likely be pursued in the Doubler design. An explicit choice may be necessary in order to limit the design requirements of the correction coils and the option of third integer may thus be ruled out.

Slow extraction over times of 1 to 10 sec require ripple-control regulation of almost all devices that can effect the beam phase space, longitudinal or transverse, or the mean values of momentum and tune. Thus, although the main magnet power supply is the most obvious source and has been designed to a ripple and regulation tolerance of 10^{-5} (probably not good enough), if the chromaticity is near zero it could have a reduced effect because the quads and bends are in series. On the other hand, ripple and bad regulation in the correction quads or octupoles, for instance, will have no compensating features and will again require regulation and ripple suppression as well as can be done (10^{-5} - 10^{-6}). Similar arguments are true to a lesser extent for sextupole corrections. For the correction-quadrupole system, it seems that uniform slow extraction prohibits the use of individually controlled correction coils and forces the use of two series systems for tune adjustment and other devices for harmonic adjustment.

Good slow extraction also requires the control of beam instabilities. Coherent synchrotron oscillations will effect the spill as will non-uniform bunch length.

On the whole, the statement that superconducting magnets have no ripple and consequently the spill will be very good has no basis in reality. It will be difficult to obtain a good spill duty factor for 10-sec spill times. Detailed analysis of the spill problem must still be done.

Beam losses from slow extraction occur because some fraction (approximately 2%) of the extracting protons hit the first extraction element, the electrostatic septum. Both secondary particles and protons with reduced momentum or with scattering angles that cannot be intercepted by some collimator arrangement will hit and shower in the Doubler magnets downstream of the septum. Most of these particles will be distributed uniformly enough along the Doubler magnets so that the local heating is not sufficient to quench the magnets. On the other hand, photons from π^o decay traveling in a straight line will interact in a local region of the Doubler magnets, because those magnets bend away from the straight section. Design of shielding arrangements of conventional bending magnets and collimators is being studied.

The electrostatic septum does not split the beam cleanly so some protons will also strike the second extraction device, a septum magent located one-sixth of the ring away. Beam spray from this source is not as great a problem.

h. Beam Loss in the Superconducting Magnets. Small amounts of beam hitting and showering in the Doubler magnets can elevate the temperature of the conductor sufficiently so that the magnet will quench. Probably 2-3 · 10^7 particles at 1000-GeV or 10^9 particles at 150 GeV are sufficient to quench the magnets if delivered in a short spike (< 1 msec), and four times this if delivered over one sec.

Near peak excitation, the allowed energy deposition becomes very small. As it is most likely that beam will be lost on center line, the tolerable temperature rise of the conductor will be about 0.5K. Operation of the accelerator at peak excitation will be very difficult unless adequate shielding is provided. Beam-loss limitations will still be a problem at lower excitation.

Design criteria for tolerable loss levels are based on $\frac{1}{2}$ mJ/gm for spikes of short duration and 4 mW/gm for uniform loss over times of the order of 1 sec. Calculations show that 1000-GeV beam hitting the front edge of the magnet vacuum chamber will typically produce 2 GeV/cm^3 in the coil per interacting particle.* If, however, the vacuum chamber is moved inward from direct contact with the coils by 0.5 cm, a reduction in energy deposition of a factor of 6 is obtained. If a plug is inserted in the magnet, a further reduction of 3.5 is obtained. Thus by modifying the vacuum chamber throughout the accelerator it seems possible to harden the average magnet by a factor of 6. At specific locations, such as downstream of extraction septa or at medium straight sections where aperture-limiting collimators could be inserted, a factor of 20 could be gained. It is estimated that 4 x 10^{10} interacting particles/sec could be scraped in this way with a medium straight-section scraper. Energy deposition in magnets following the extraction-septum long straight section may even be tolerable. The use of some 4-in. diameter magnets fitted with shielding plugs may prove to be very useful in special locations.

The design work on bending magnets and collimators in the long straight section behind the electrostatic septum to shield the Doubler magnets from neutral beam and to sweep away low-energy secondaries has not yet produced satisfactory results. The problem is associated with relatively high energy scattered protons.

5. Colliding Beams

a. Proton-Proton. The pp option calls for very little design effort in the Doubler itself. Much more work is necessary in the Main Ring. Major components are the kissing

* (10^8 particles, each depositing energy of 1 GeV/cm^3, are equivalent to 2 mJ/gm.)

magnets of the interaction region, which bring the main ring and doubler beams together. These magnets give a total of about 400 kG-m of field for each beam. Expected field quality is such that corrections will probably be necessary in the Main Ring but not in the Doubler. The Main-Ring magnets adjacent to the straight section must be rolled and lowered to bring the Main-Ring beam into the straight section with a down bend and at lower elevation. No work has been done to analyze the effect of coupling and vertical momentum dispersion. A $\beta^* = 2.5$-m region for the Main Ring has previously been worked out, but no analysis of necessary corrections have been done ($\beta_{max} \approx 1000$ m, $\eta_{max} \approx 13$ m). Backward injection and operation of the Main Ring is of course necessary. The Doubler interaction region β^* of approximately 10 m is easy to obtain and should not present any problems.

b. Proton-Antiproton. Many of the aspects of the Doubler design associated with $\bar{p}p$ interactions have already been discussed. Injection, abort, rf and beam detectors all require special consideration. Storage times of 3 hours are required. Pressures of 10^{-8} Torr in the straight sections should give vacuum lifetimes of approximately 10 hours. It is expected that we will use electrostatic beam separators and space at appropriate locations must be found for them.

Here again, a complete analysis of the effects of low β must be made, the chromaticity correction determined, the third-integer stopband evaluated, and β^* η^* (and also β and η around the ring) determined as functions of momentum. The need for harmonic sextupole corrections can then be analyzed. Changes in tune, β and η must be determined so that the effect on the abort and beam-scraper systems can be analyzed. Off-momentum effects may not be as important as one would first think because of the relatively small momentum spread of the beam.

The $\bar{p}p$ option calls for debunching of the proton beam on the 21st harmonic in the Main Ring. We expect in this way to get 10^{11} protons per rf bunch. Problems associated with instabilities of the debunched beam, momentum spread and rebunching rf parameters must be evaluated.

6. Layout

An attempt at layout can be undertaken.

a. Extraction. Extraction channel must be at A_o, a high-β straight section.

Extraction septum is at F_o (87^o phase advance). Appropriate radiation shielding will use up about 28 m of the straight section length. A problem is that the Main Ring RF is located here. Radioactivity at the cavities is a severe problem.

b. Abort. Choose the conservative abort design, namely the one where the two kickers are separated by one-third of the circumference, with the abort channel and dump block in the straight section halfway between. For $\bar{p}$ colliding beams, the rf bunches can be distributed over no more than two-thirds of the ring and the interaction region must be opposite the abort straight section. The abort must be in E0 and the interaction region in B0. The proton abort kicker (6 m length) is at the upstream end of D0, and the $\bar{p}$ abort kicker (6 m) is at the downstream end of F0.

At this point, all of A0, B0, E0 are used up. C0 has not been used and 16 m of F0 and 44 m of D0 remain.

c. RF and Injection. The rf takes 28 meters overall with four 1.4 m spaces which might be used for beam detectors, etc. The rf could be split into fractional units but it is clearly more efficient to have it all together. The small diameter of the cavities allows for injection in one direction and all the rf in one straight section. The only straight section which is free is C0. Backward injection must go here because the proton abort kicker would be in the way in D0.

Figure 1 shows the layout of the basic elements. Note that it would be very difficult to locate the main ring rf anywhere else. Devices that are not shown are as follows:

(i) Pulsed quads for fast extraction (1 m long). They must go in the 6-m-straight adjoining the long straight section (48 location) at as many locations as possible (at least two locations with opposite phases)

(ii) Pulsed bumps (1.5 m) at F0 and A0 for extraction. These use the 48 location and some long straight section space.

(iii) A high-frequency cavity (Landau cavity) for bunch stability (4 m) can go anywhere, preferably near the rest of the rf or near the Main Ring rf.

(iv) Beam separators for colliding $\bar{p}p$'s

(v) Horizontal and vertical beam detectors, slow and fast dampers for transverse instabilities and rf feed-back, and fast intensity detectors for longitudinal phase monitoring.

(vi) Collimators and scrapers for horizontal, vertical and off-momentum collimation. Off-momentum collimation will be done at the medium straight sections, and vertical at the extraction septum straight section.

A very different layout can be obtained with some different starting assumptions. Put the extraction septum in straight section D (261° phase advance to A0). Put the $\bar{p}$ abort stopping block at the downstream end of A0 and take advantage of the larger vertical β here. Put both abort kickers in B0 and let both kick both beams. Now the full ring can be used for $\bar{p}$'s. Put both forward and backward injection lines in B0 between the kickers. This will lower the injection energy to 100 GeV. The Doubler rf can now stay at F0 below the Main Ring rf and the layout now looks like Figure 2. Note that be removing the extraction septum and shielding, a second interaction region can be obtained. No evaluation of the feasibility of this layout has been made and it is included here only as an indication of the still preliminary nature of the design and the necessity for much more work before final construction decisions are made.

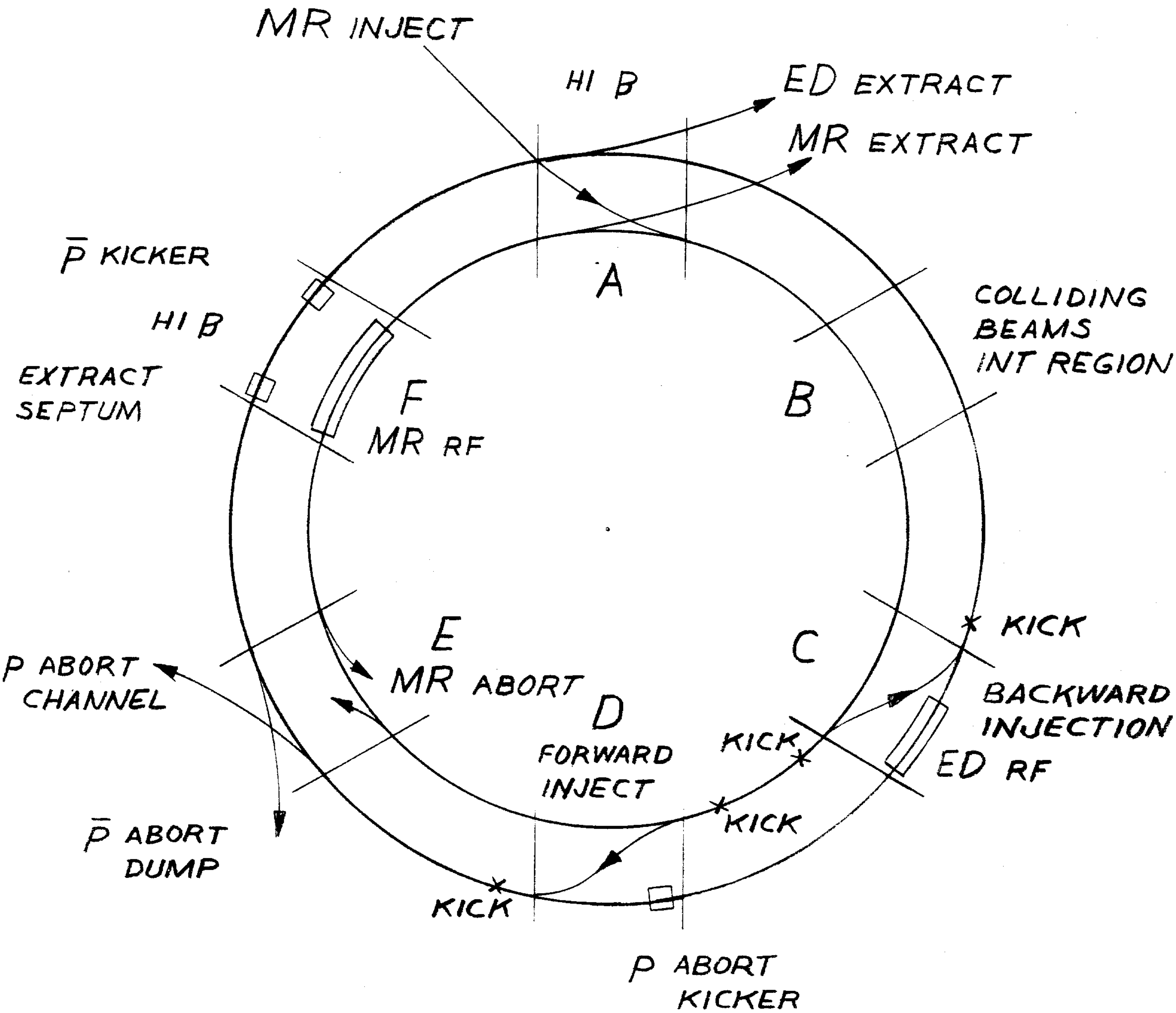

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FIG 1

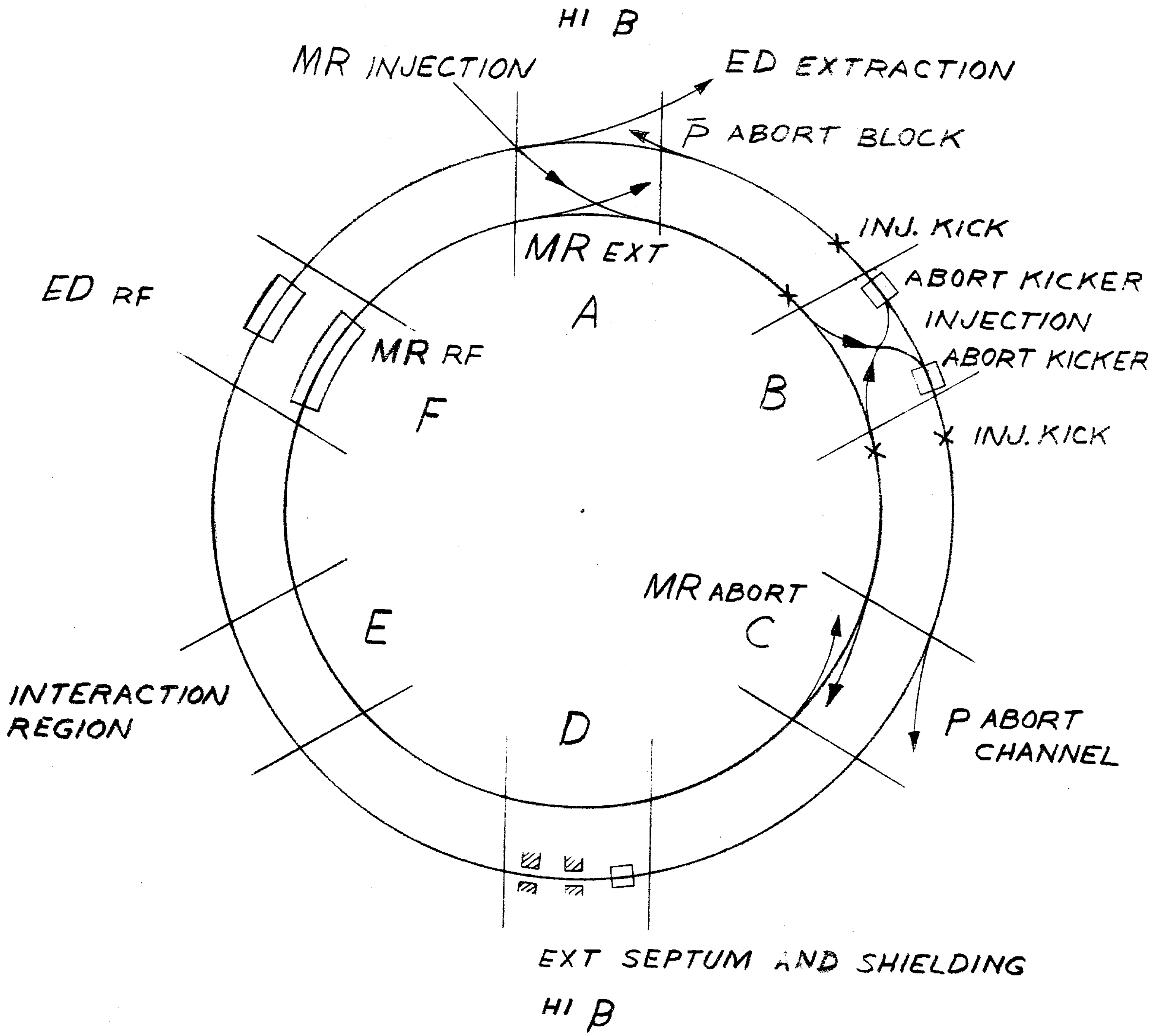
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FIG 2